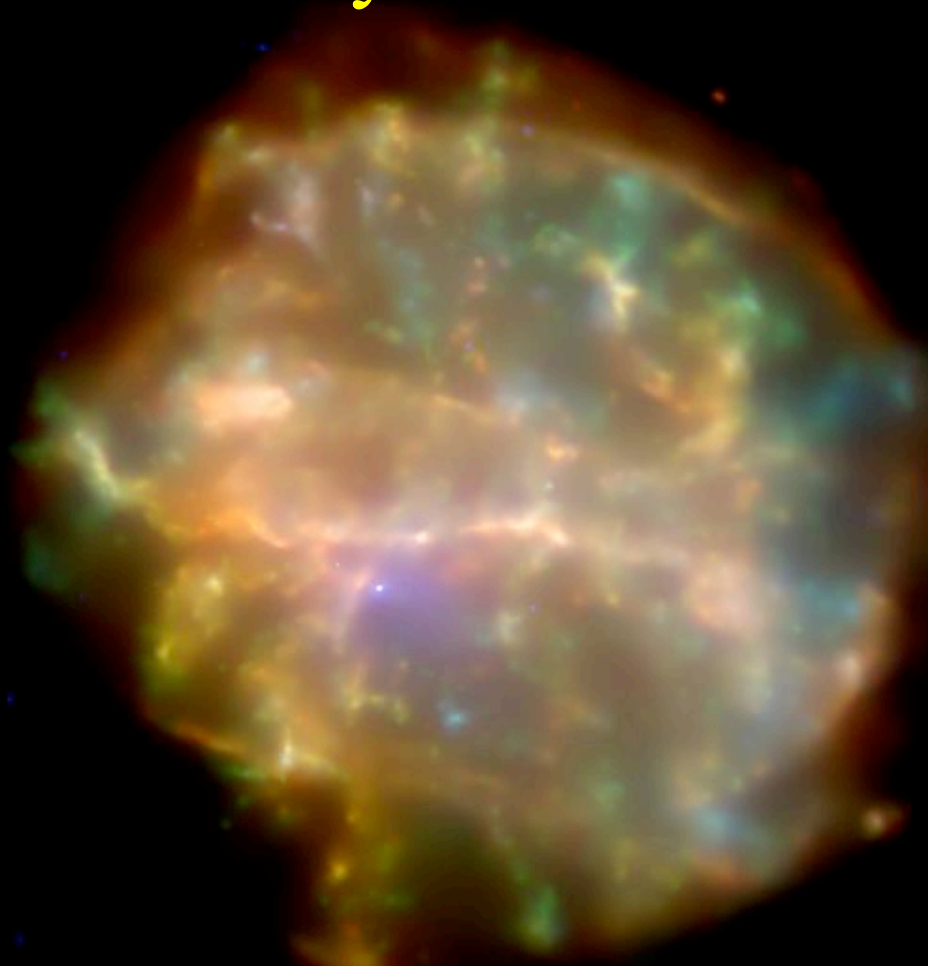
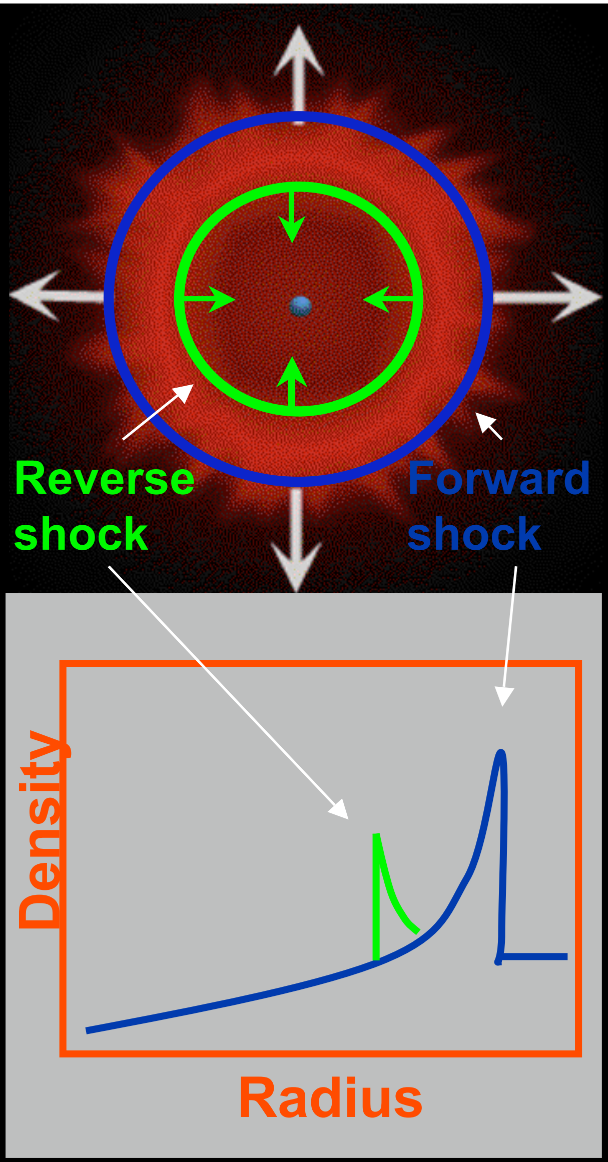
X-ray Studies of



Composite Supernova Remnants

Patrick Slane

Harvard-Smithsonian Center for Astrophysics

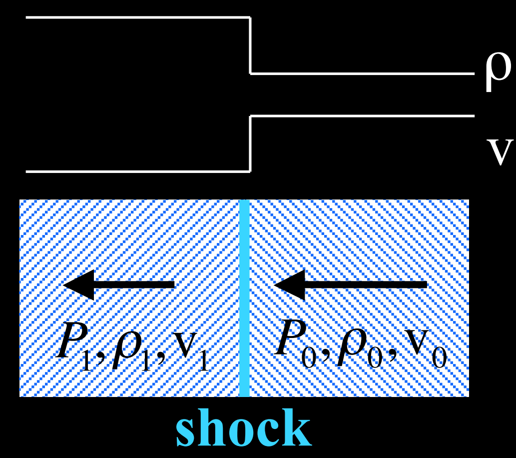


Supernova Remnants

- **Explosion blast wave sweeps up CSM/ISM in forward shock**
  - **spectrum shows abundances consistent with solar or with progenitor wind**

- **As mass is swept up, forward shock decelerates and ejecta catches up; reverse shock heats ejecta**
  - **spectrum is enriched w/ heavy elements from hydrostatic and explosive nuclear burning**

Shocks in SNRs



- Expanding blast wave moves supersonically through CSM/ISM; creates shock
  - mass, momentum, and energy conservation across shock give (with γ=5/3)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 = 4\rho_0$$

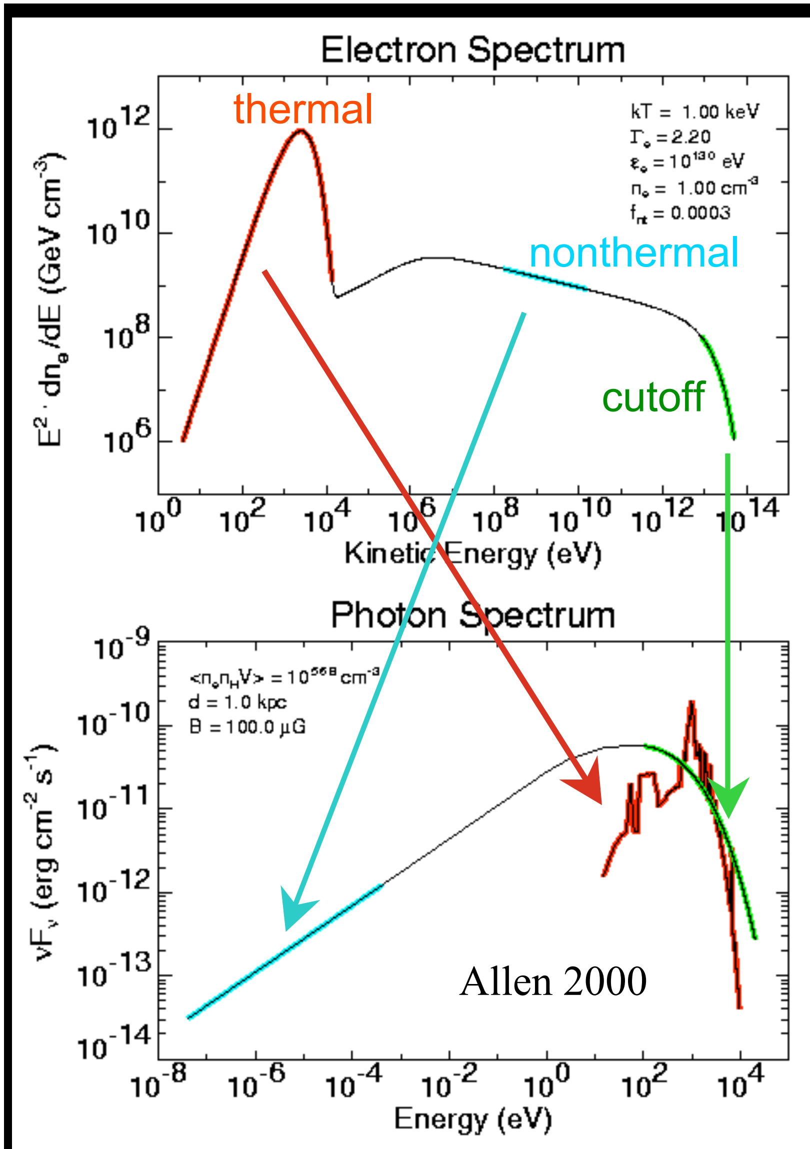
$$v_1 = \frac{\gamma-1}{\gamma+1}v_0 = \frac{v_0}{4}$$

$$v_{ps} = \frac{3v_s}{4}$$

$$T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2}\frac{\mu}{k}m_H v_0^2 = 1.3\times10^7 v_{1000}^2\ \mathrm{K}$$

X-ray emitting temperatures

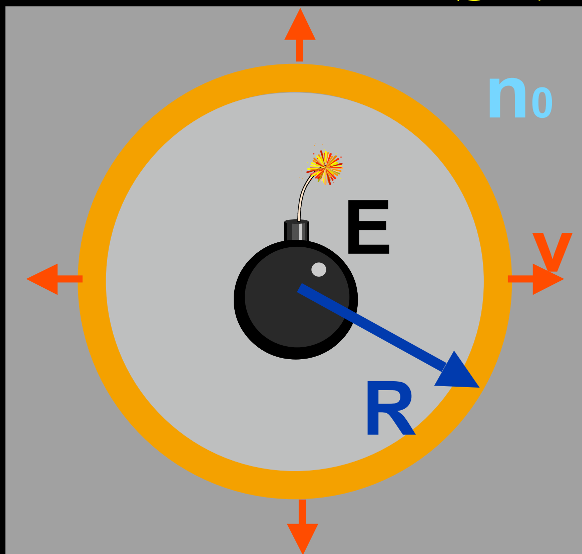
- Shock velocity gives temperature of gas
  - note effects of electron-ion equilibration timescales
- If another form of pressure support is present (e.g. cosmic rays), <u>the temperature will be lower than this</u>



Shocked Electrons and their Spectra

- Forward shock sweeps up ISM; reverse shock heats ejecta
- Thermal electrons produce line-dominated x-ray spectrum with bremsstrahlung continuum
  - yields kT, ionization state, abundances
- nonthermal electrons produce synchrotron radiation over broad energy range
  - responsible for radio emission
- high energy tail of nonthermal electrons yields x-ray synchrotron radiation
  - rollover between radio and x-ray spectra gives exponential cutoff of electron spectrum, and a limit to the energy of the associated cosmic rays
  - large contribution from this component modifies dynamics of thermal electrons

SNR Evolution: The Ideal Case



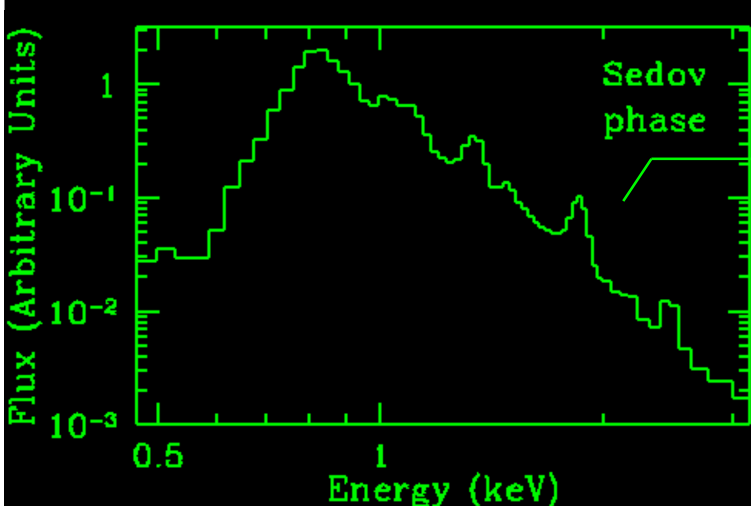
- **Once sufficient mass is swept up (> 1-5 M$_{ej}$) SNR enters Sedov phase of evolution**

$$t_{yr} = 470 R_{pc} T_7^{-1/2} \qquad \frac{E_{51}}{n_0} = 340 R_{pc}^5 t_{yr}^{-2}$$

- **X-ray measurements can provide temperature and density**

$$EM = \int n_H n_e dV \qquad T_x = 1.28 T_{shock}$$

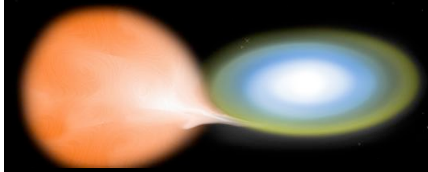
from spectral fits



- **Sedov phase continues until kT ~ 0.1 keV**

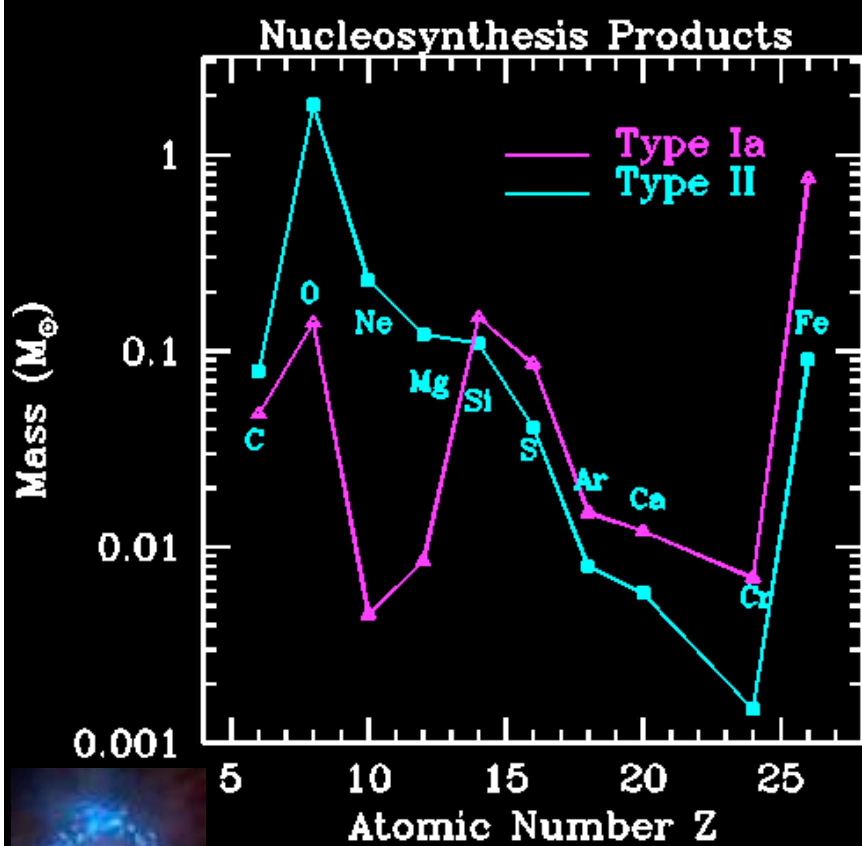
$$t_{rad} \approx 2.4 \times 10^4 \left(\frac{E_{51}}{n_0}\right)^{1/3} yr$$

SNRs: Tracking the Ejecta



Type Ia:

- Complete burning of 1.4 $M_\odot$ C-O white dwarf
- Produces mostly Fe-peak nuclei (Ni, Fe, Co) with some intermediate mass ejecta (O, Si, S, Ar…)
  - very low O/Fe ratio
- Si-C/Fe sensitive to transition from deflagration to detonation; probes density structure
  - X-ray spectra constrain burning models
- Products stratified; preserve burning structure

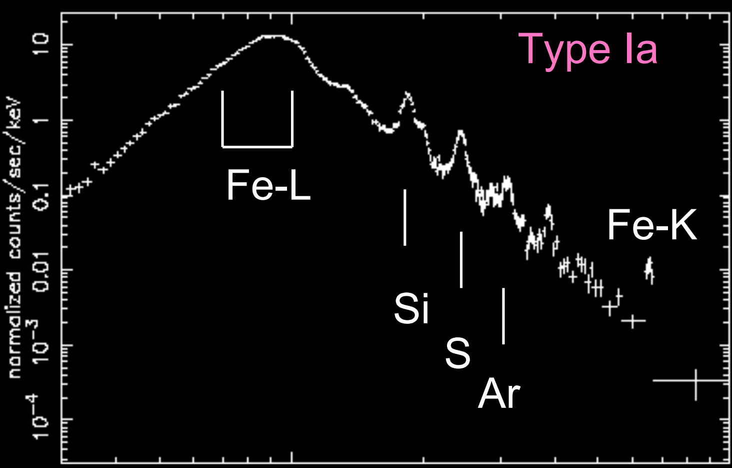


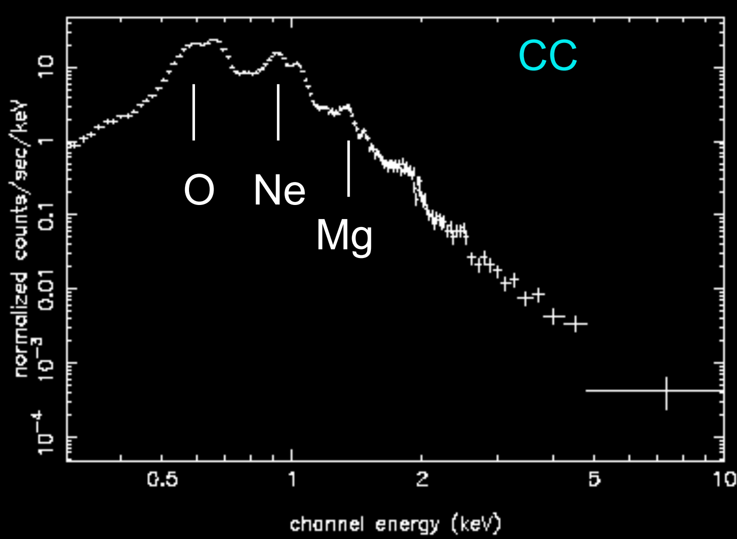
Core Collapse:

- Explosive nucleosynthesis builds up light elements
  - very high O/Fe ratio
  - explosive Si-burning: "Fe", alpha particles
  - incomplete Si-burning: Si, S, Fe, Ar, Ca
  - explosive O-burning: O, Si, S, Ar, Ca
  - explosive Ne/C-burning: O, Mg, Si, Ne
- Fe mass probes mass cut
- O, Ne, Mg, Fe very sensitive to progenitor mass
- Ejecta distribution probes mixing by instabilities

T

SNRs: Tracking the Ejecta





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  - explosive Ne/C-burning: O, Mg, Si, Ne

T

- Fe mass probes mass cut
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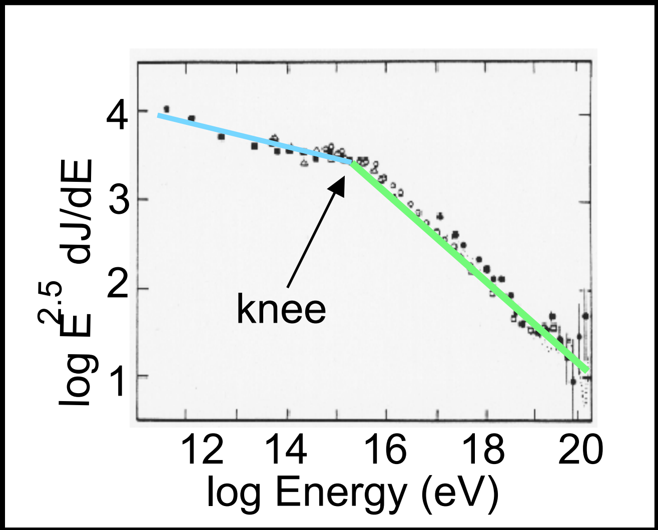
- Ejecta distribution probes mixing by instabilities

Synchrotron Emission from SNRs

- Cosmic ray spectrum extends to $E > 10^{20}\,\mathrm{eV}$
- Break (or "knee") in spectrum at about $10^{15}\,\mathrm{eV}$
  - energy density below knee is ~consistent with energy input from SNRs
  - PL index is consistent with that for Fermi acceleration

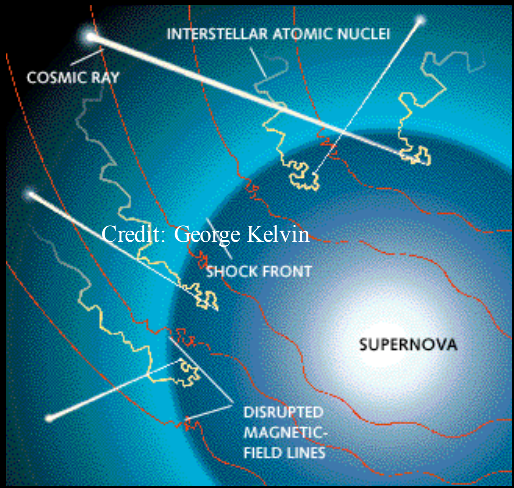


- Synchrotron Radiation:
  - for typical fields, radio emission is from GeV electrons
  - for X-rays, $\nu \geq 10^{18}\,\mathrm{Hz}$ ⟶ >TeV electrons
  - PL spectra imply PL particle spectrum

$$dN = KE^{-\alpha}dE$$

gives

$$f_\nu \propto \nu^{\left(-\frac{\alpha-1}{2}\right)}$$



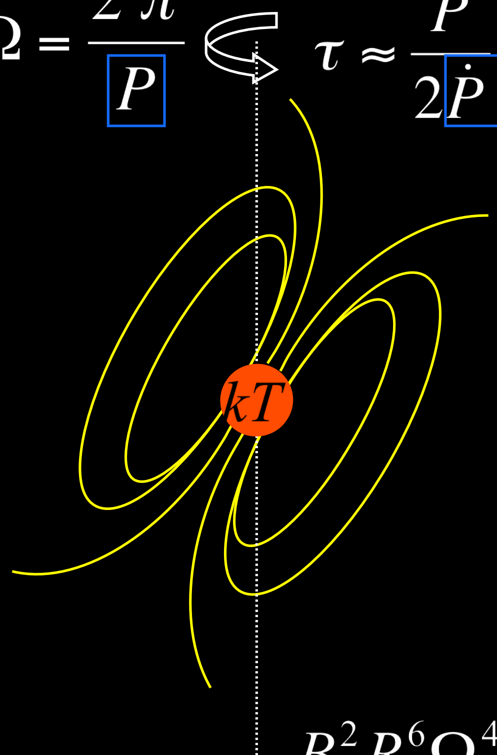
  - shell-type SNRs have

$$f_\nu \propto \nu^{(-0.6)}$$

$\therefore \alpha = 2.2$ similar to CR spectrum

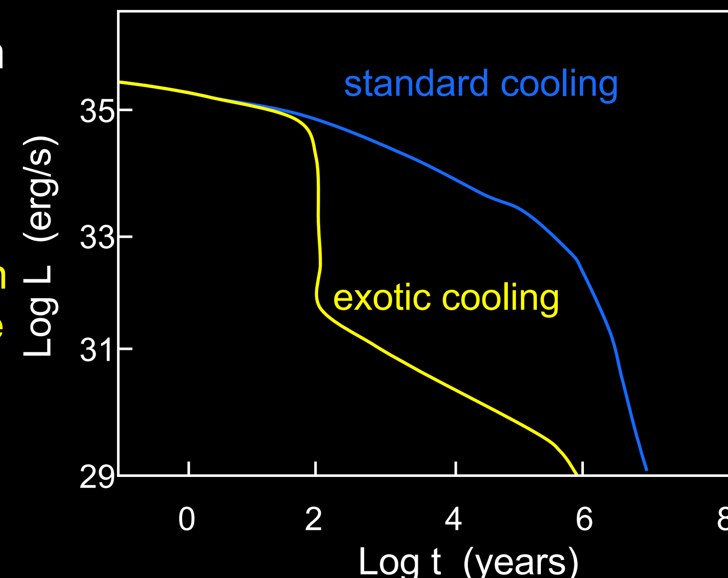
(Some) Physics of Neutron Stars

$$\Omega = \frac{2\pi}{\boxed{P}} \qquad \tau \approx \frac{P}{2\boxed{\dot{P}}}$$



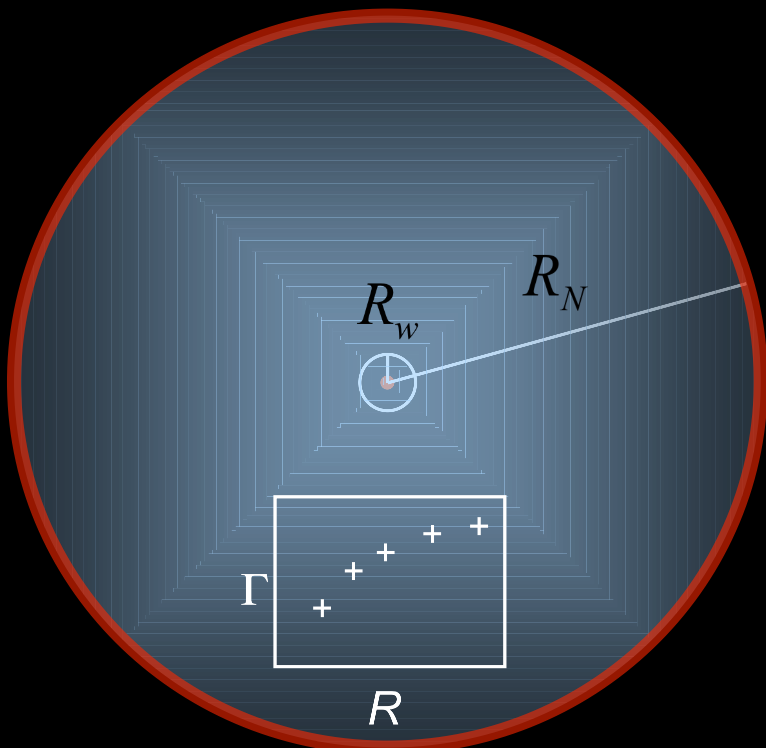
$$\dot{E} = I\Omega\dot{\Omega} = \frac{B^2 R^6 \Omega^4}{6c^3}$$

- **Pulsation characteristics yield measurements of energy loss rate, age, and magnetic field strength**
  - under assumptions of mass, radius, dipole field
- **Thermal emission from NS surface constrains cooling models**
  - possible exotic processes such as pion condensation
  - constrain equation of state at ultra-high density
  - atmosphere effects probe opacity in strong B-fields; lines give M/R for NS



- **Pulsar produces relativistic wind with wound-up toroidal magnetic field**
  - jets may form along rotation axis; related to pulsar kicks?
  - shocked outflowing wind forms synchrotron nebula
  - nebula structure reveals geometry, wind dynamics, ejecta

Pulsar Wind Nebulae



- **Pulsar wind inflates bubble of energetic particles and magnetic field**
  - pulsar wind nebula
  - synchrotron radiation; at high frequencies, index varies with radius (burn-off)

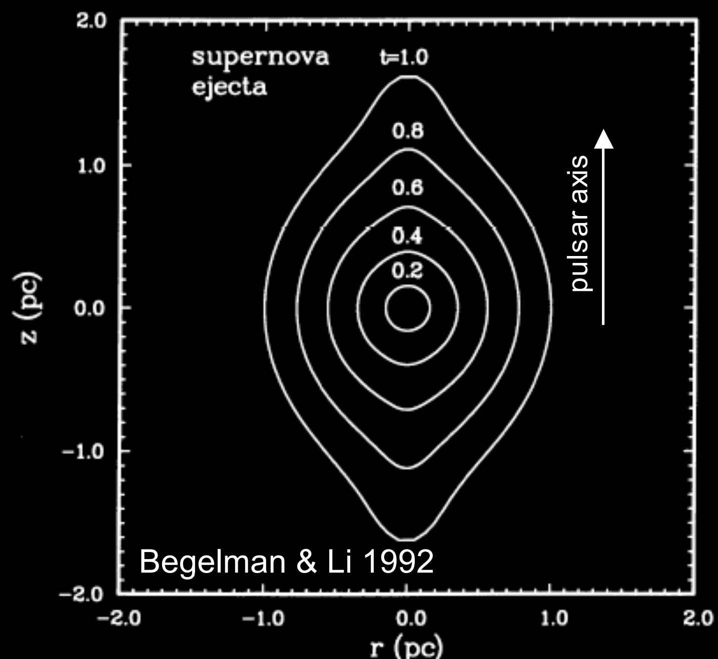
- **Expansion boundary condition at forces wind termination shock at**
  - wind goes from $v \approx c/3$ inside R_w to $v \approx R_N / t$ at outer boundary

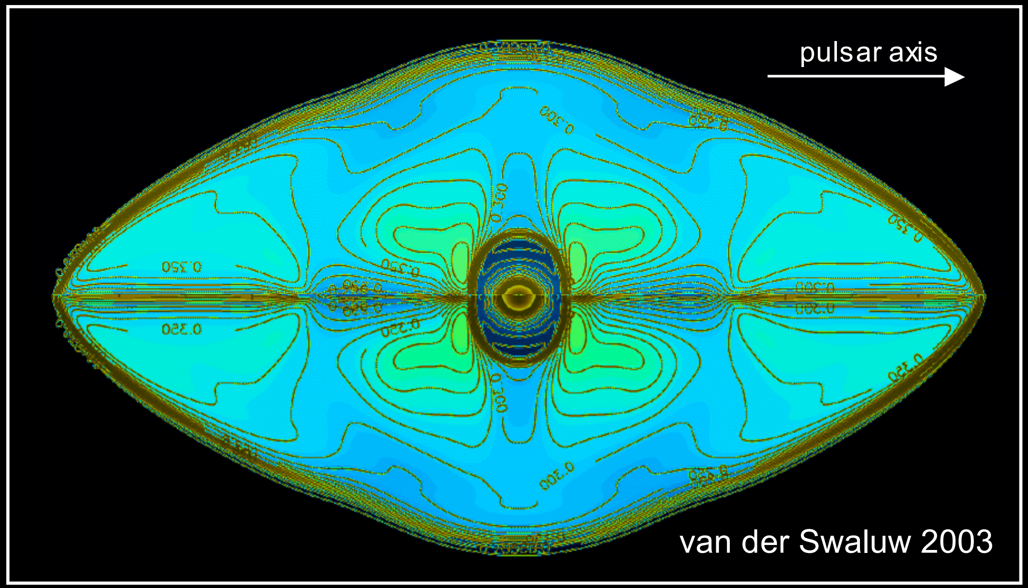
- **Pulsar wind is confined by pressure in nebula**

$$\frac{\dot{E}}{4\pi R_w^2 c} = P_{neb}$$

obtain by integrating radio spectrum

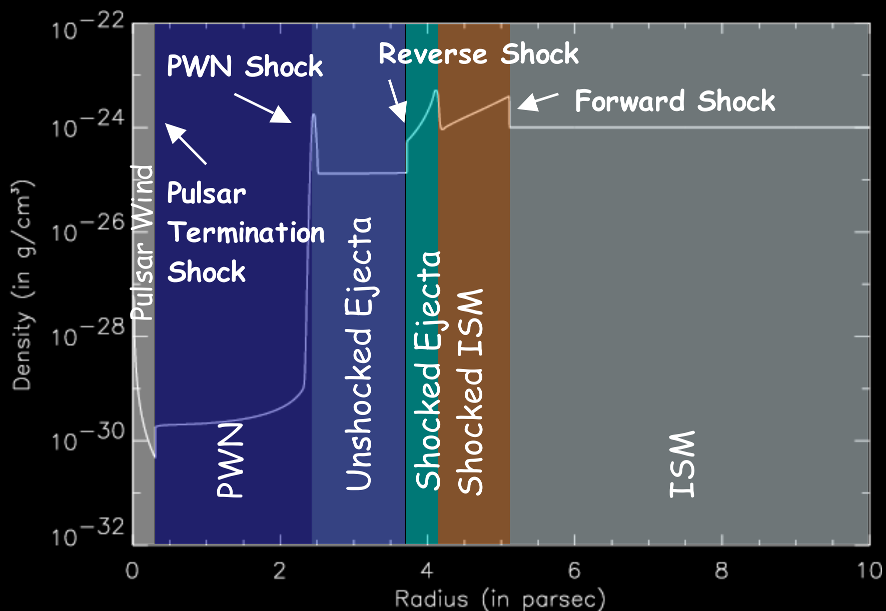
Elongated Structure of PWNe

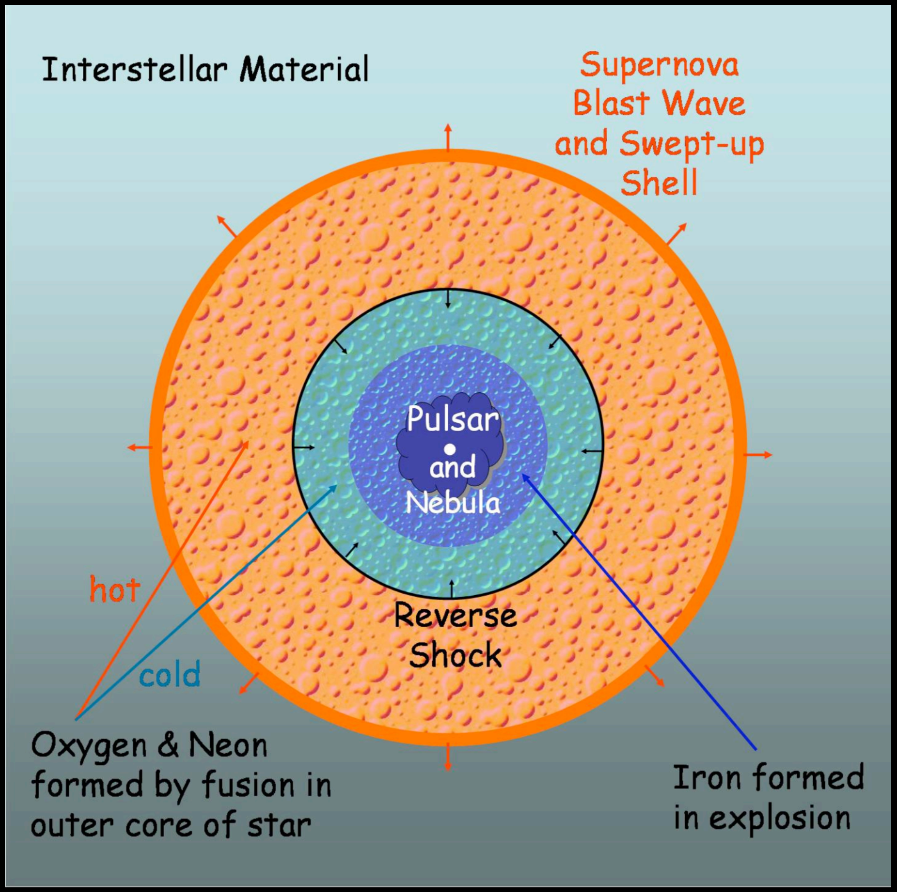




- **Dynamical effects of toroidal field result in elongation of nebula along pulsar spin axis**
  - profile similar for expansion into ISM, progenitor wind, or ejecta profiles
  - details of structure and radio vs. X-ray depend on injection geometry and B
- **MHD simulations give differences in detail, but similar results overall**
  - B field shows variations in interior
  - turbulent flow and cooling could result in additional structure in emission

Putting it Together: Composite SNRs

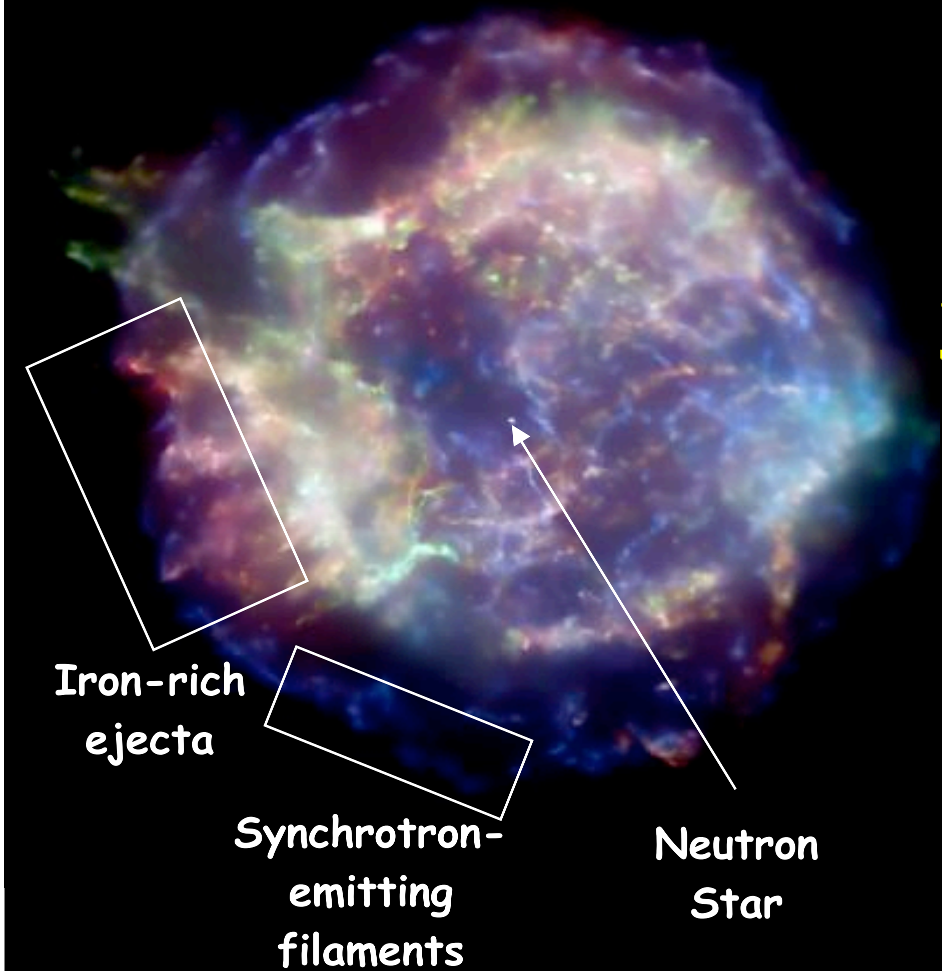




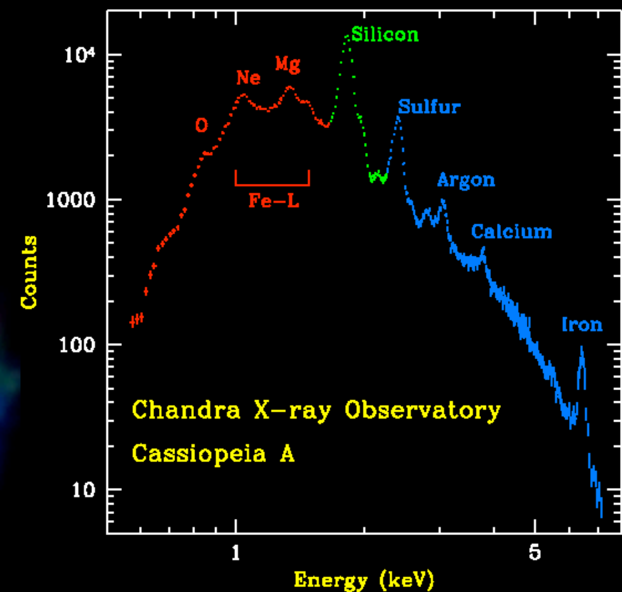
- **Pulsar Wind**
  - sweeps up ejecta; termination shock decelerates flow; PWN forms

- **Supernova Remnant**
  - sweeps up ISM; reverse shock heats ejecta; ultimately compresses PWN

Cassiopeia A: A Young Core-Collapse SNR



Hughes, Rakowski, Burrows, & Slane 2000, ApJ, 528, L109
Hwang, Holt, & Petre 2000, ApJ, 537, L119



<u>ACIS-S Observation:</u>

3-color image in soft/medium/hard bands (ds9)

Spectra of entire SNR and discrete regions (acisspec)

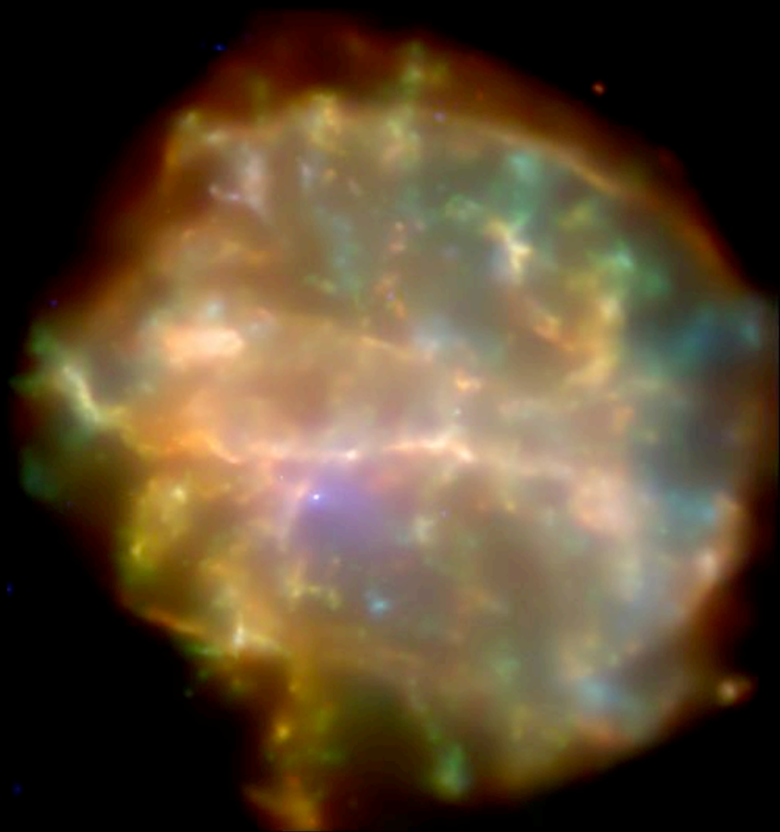
Spectral fitting (xspec/sherpa, NEI models w/ variable abundances; power law model; blackbody model)

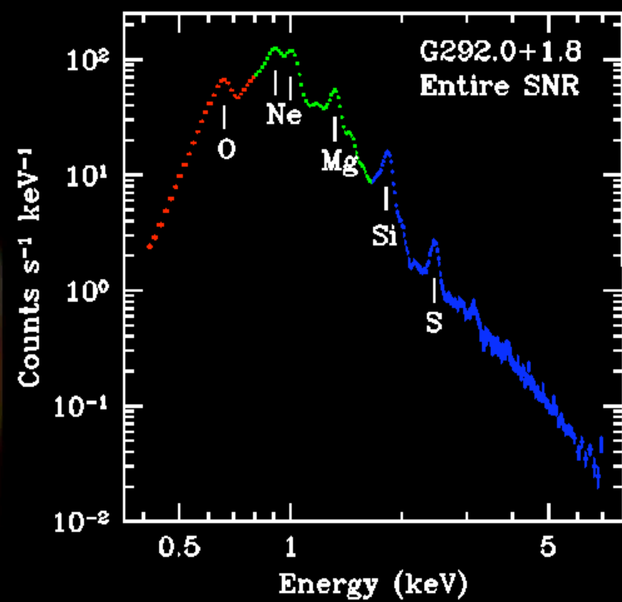
<u>HRC Observation:</u>

Timing studies (axbary, FFT)

- **Complex ejecta distribution**
  - Fe formed in core, but found near rim
- **Nonthermal filaments**
  - cosmic-ray acceleration
- **Neutron star in interior**
  - no pulsations or wind nebula observed

G292.0+1.8: O-Rich and Composite





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3-color image in soft/medium/hard bands (ds9)

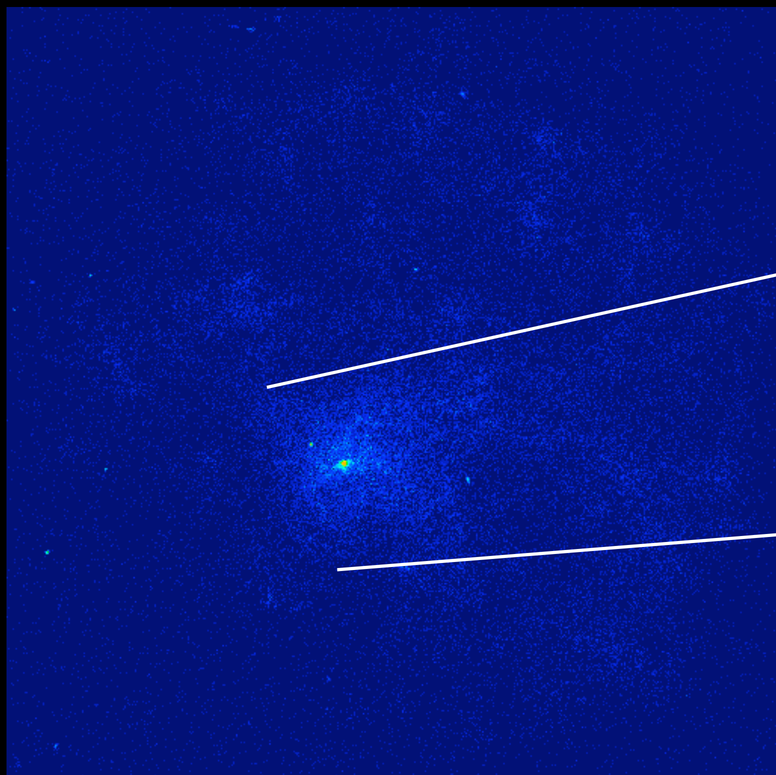
Spectrum of entire SNR (acisspec)

Spectral fitting (xspec/sherpa, NEI models w/ variable abundances

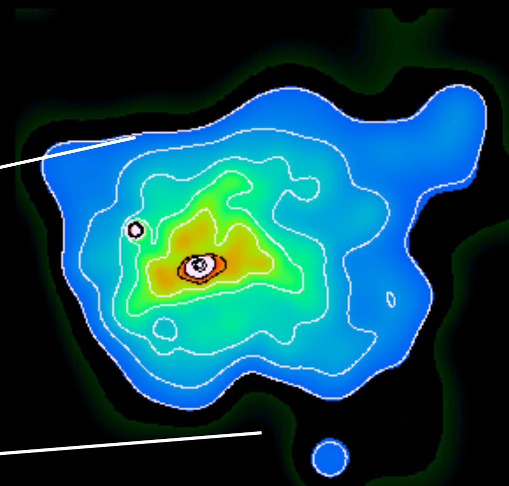
- Oxygen-rich SNR; massive star progenitor
  - dynamical age ~2000 yr
  - O & Ne dominate Fe-L, as expected

Park, et al. 2002, ApJ, 564, L39

G292.0+1.8: O-Rich and Composite



Hughes, et al. 2001, ApJ, 559, L153



ACIS-S Observation:

Hard-band image (ds9)

Spectrum of PWN (acisspec)

Spectral fitting (xspec/sherpa,; power law model)

HRC Observation:

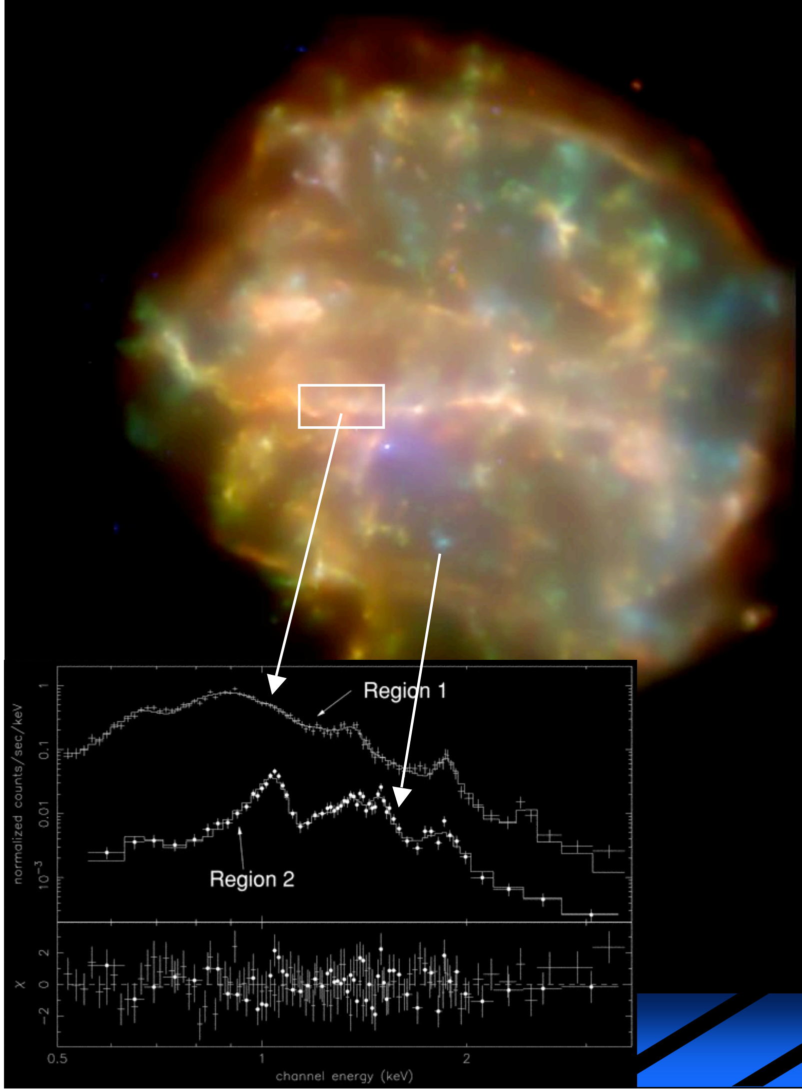
Timing studies (axbary, FFT)

- Compact source surrounded by diffuse emission seen in hard band
  - pulsar (Camillo et al. 2002) and PWN
  - 135 ms pulsations confirmed in X-rays

- Compact source extended
  - evidence of jets/torus?

Hughes, Slane, Roming, & Burrows 2003, ApJ

G292.0+1.8: Sort of Shocking…



- Individual knots rich in ejecta
- Spectrum of central bar and outer ring show ISM-like abundances
  - relic structure from equatorially-enhanced stellar wind?
- Oxygen and Neon abundances seen in ejecta are enhanced above levels expected; very little iron observed
  - reverse shock appears to still be progressing toward center; <u>not all material synthesized in center of star has been shocked</u>
  - pressure in PWN is lower than in ejecta as well ➔ reverse shock hasn't reached PWN?

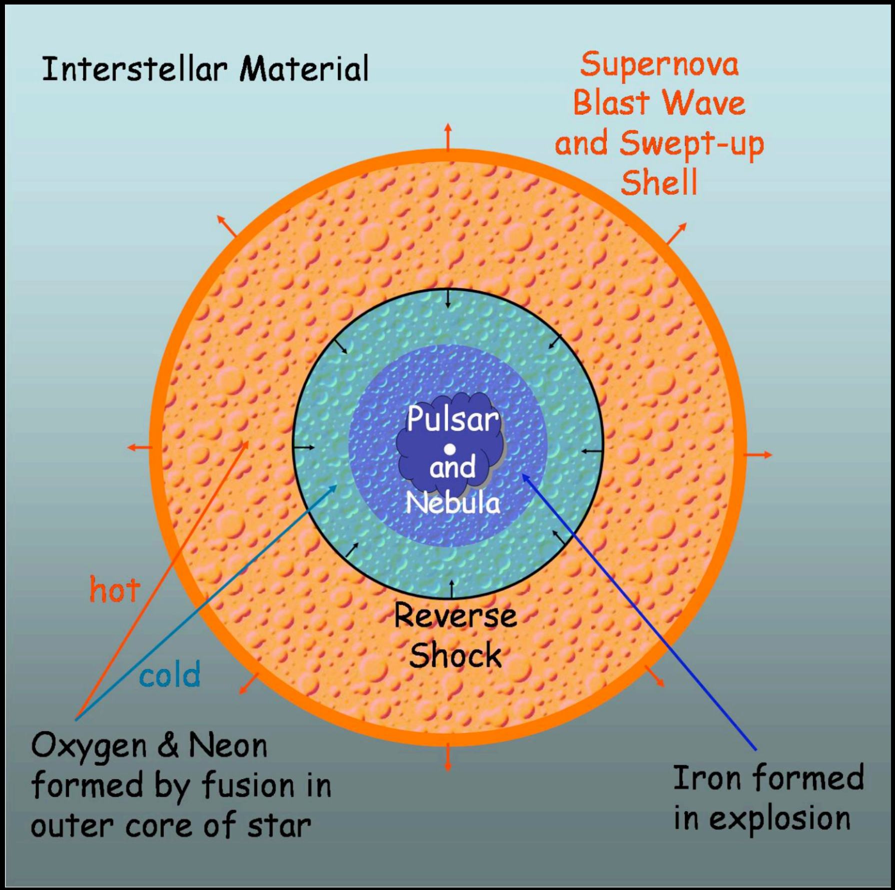
Park, et al. 2004, ApJ, 602, L33

<u>ACIS-S Observation:</u>

Spectra of discrete regions (acisspec)

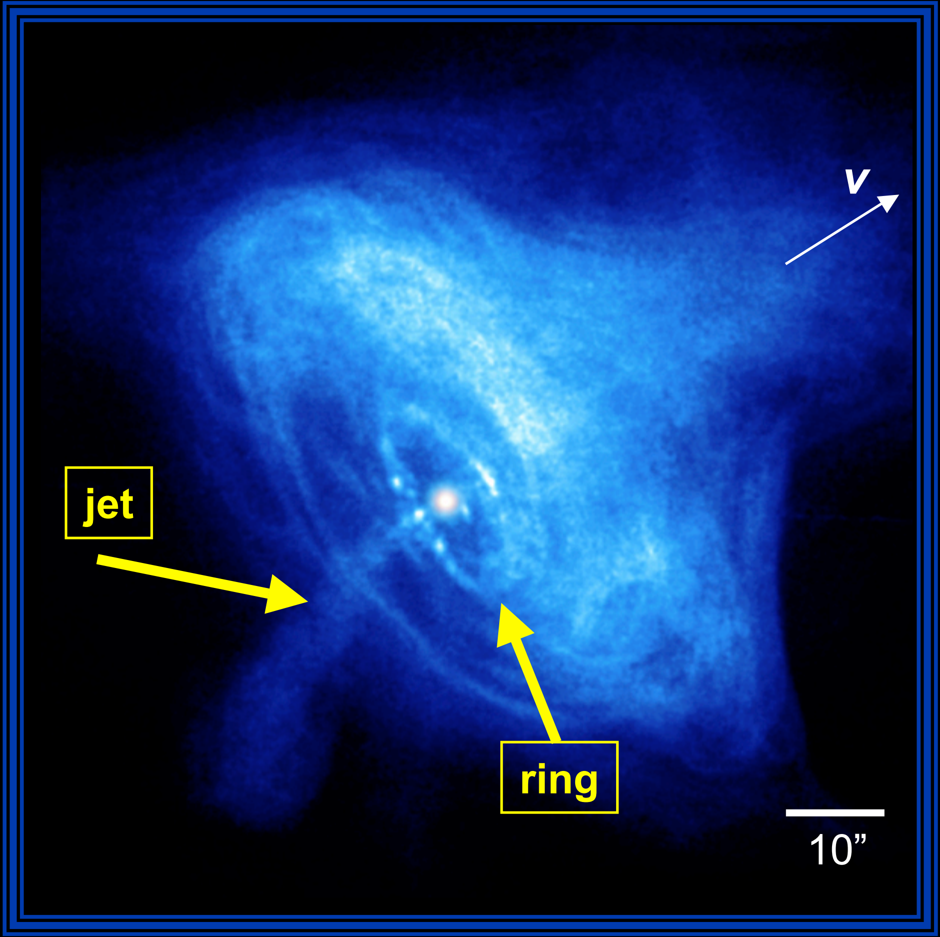
Spectral fitting (xspec/sherpa, NEI/vpshock models with variable abundances)

G292.0+1.8: Sort of Shocking…



The Crab Nebula in X-rays

- Result of explosion in 1054 AD
  - 33 ms pulsar
  - surrounding bubble of energetic particles and magnetic field
- X-ray jet-like structure appears to extend all the way to the neutron star
  - jet axis aligned with pulsar motion
- inner ring of x-ray emission associated with wind from pulsar colliding with inner nebula



Weisskopf et al. 2000

3C 58: A Young Pulsar Wind Nebula

<u>ACIS-S Observation:</u>

Merged event file from 3 pointings (merge_all)

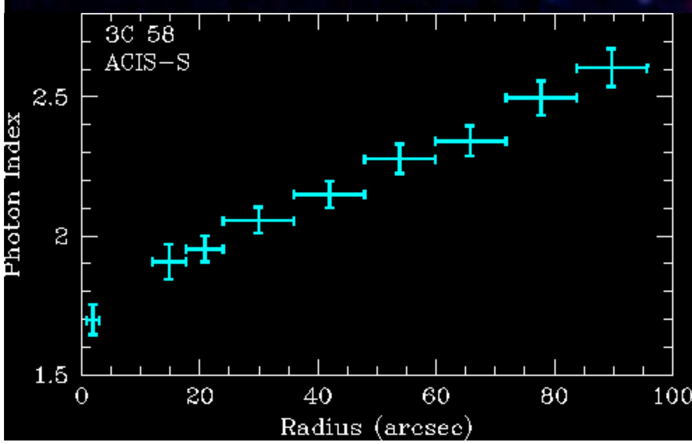
3-color exposure corrected image (dmcopy, fgauss, farith, ds9)

Spectra of PWN and discrete regions (acisspec)

Spectral fitting (xspec/sherpa,; power law, NEI, blackbody, and NS atmosphere models)

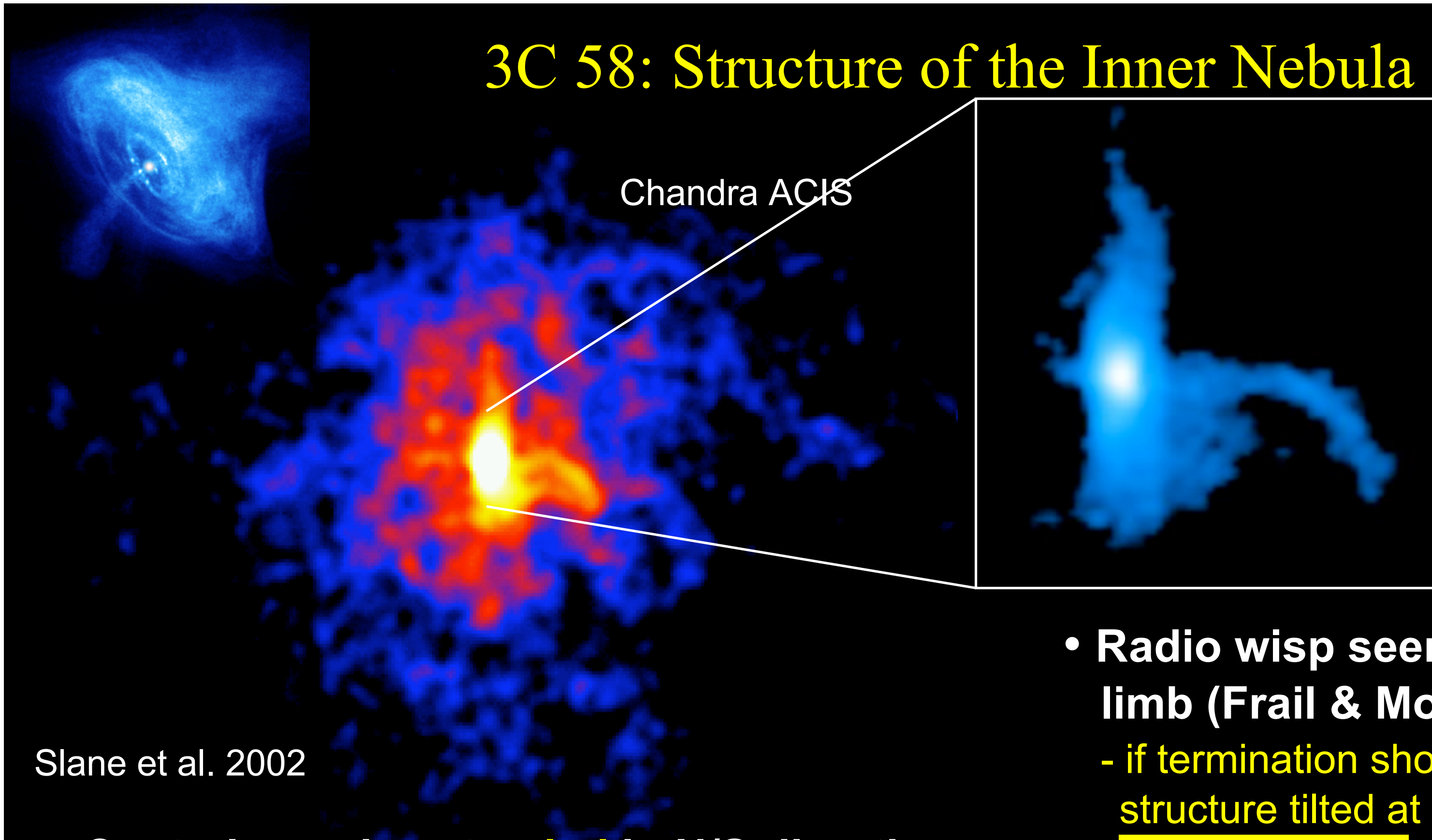
<u>HRC Observation:</u>

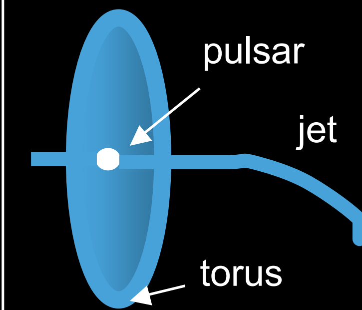
Timing studies (axbary, FFT)



- **East-West elongation suggests pulsar axis projected along this direction**
- **Spectral index variation ==> synchrotron aging**
- **Complex loops and filaments, possibly due to kink instabilities near pulsar termination shock**

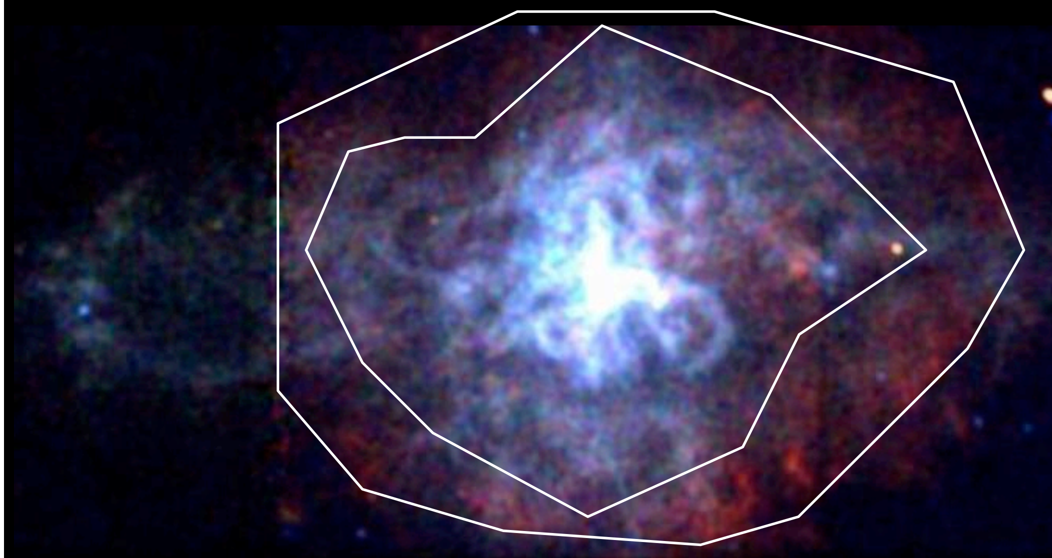
3C 58: Structure of the Inner Nebula



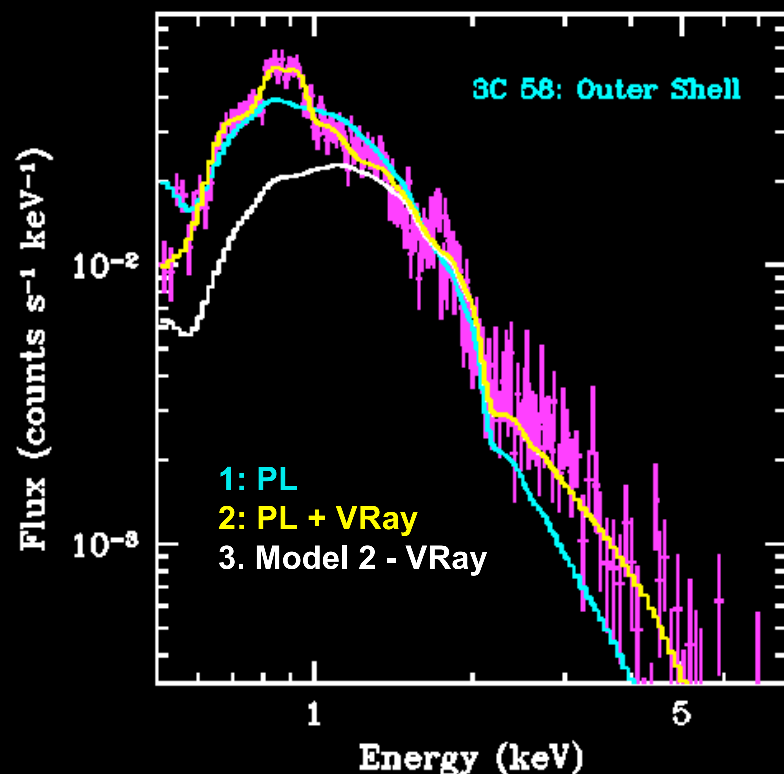


- **Central core is extended in N/S direction**
  - suggestive of inner Crab region with structure from wind termination shock zone
- **Central source is a 65 ms pulsar**
  - 3rd most energetic pulsar known in Galaxy
- **Radio wisp seen along western limb (Frail & Moffett 1993)**
  - if termination shock, suggests ring-like structure tilted at about 70 degrees
  - $\dot{E} = 4\pi c R_s^2 P_{neb}$ agrees w/ spindown
- **Suggests E-W axis for pulsar**
  - consistent with E-W elongation of 3C 58 itself due to pressure from toroidal field

3C 58: A Thermal Shell



Slane et al. 2004



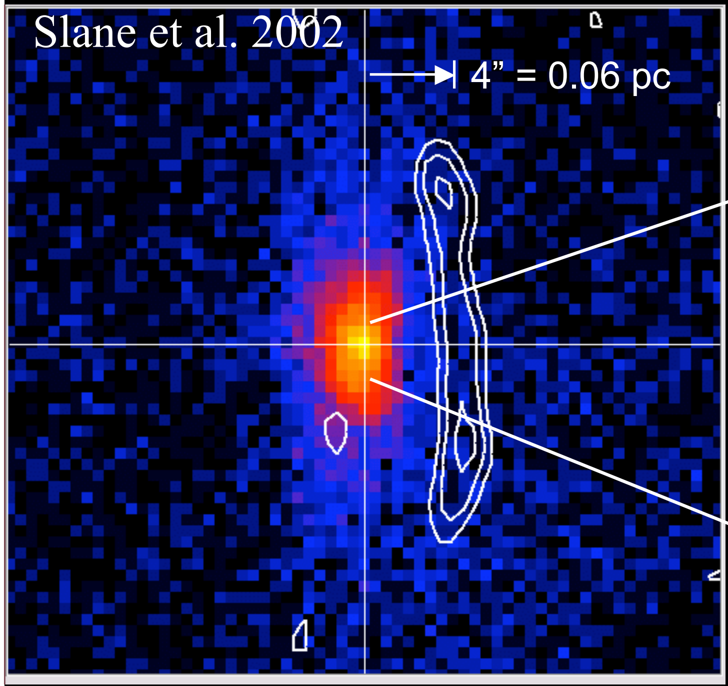
- **Outer region shows thermal emission**
  - Chandra confirms presence of a thermal shell
  - corresponds to ~0.06 solar masses
  - 3C 58 has evolved in a very low density region
- **Thermal component requires enhanced neon**
  - emission not purely from ISM; **swept-up ejecta** present

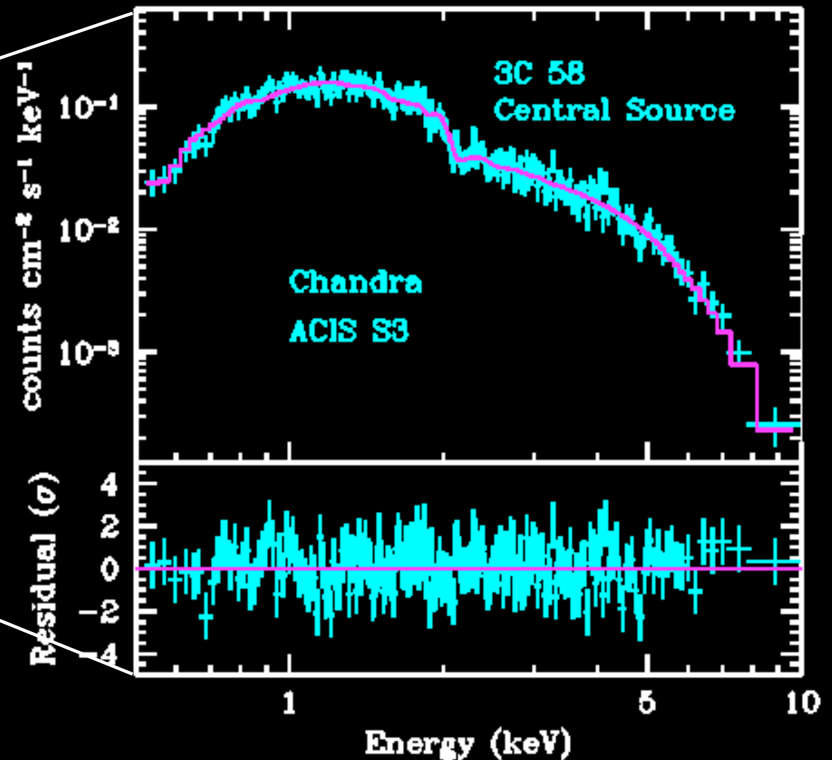
ACIS-S Observation

Extract spectrum from extended region in outer nebula (acisspec)

Fit models: power law, power law + Raymond-Smith plasma with variable abundances

3C 58: Neutron Star Spectrum





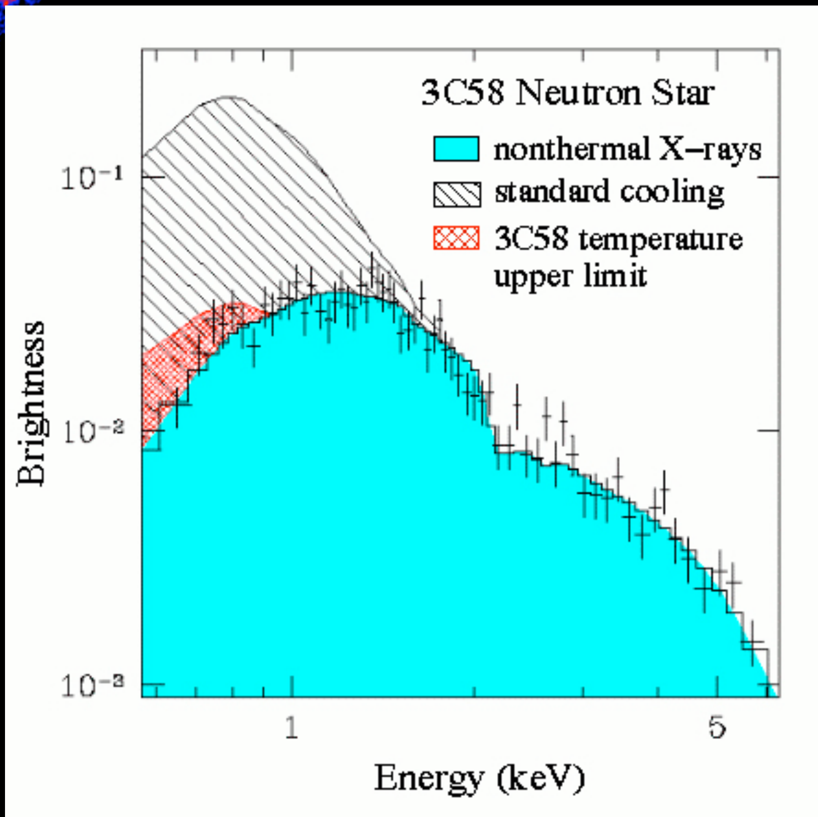
ACIS-S Observation

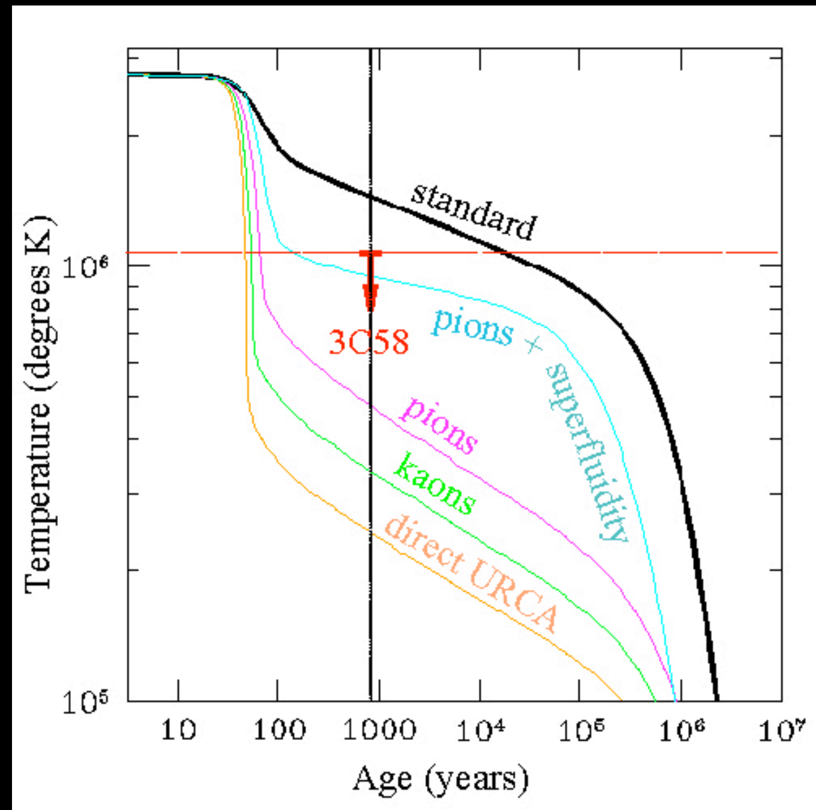
Spectrum of central point source (acisspec)

Model with absorbed power law; set limits for blackbody model with normalization for R=10 km NS, also NS atmosphere models

- **Central spectrum is a power law**
  - no (or very weak) evidence of thermal emission from surface of hot NS

PSR J0205+6449: Cooling Emission





- **Adding blackbody component leads to limit on surface cooling emission**
  - since atmosphere effects harden spectrum limit on surface temperature is conservative

- **For NS w/ *R* = 10 km,**
  - standard cooling models (e.g. Tsuruta 1998) predict higher temperature for this age
  - may indicate direct Urca or pion cooling

Composite SNRs: Summary

- **Combination of young NS and evolving SNR provides opportunity to probe a multitude of physical structures**
  - pulsar wind nebula, termination shock, jets, filaments
  - young NS cooling, pulsations
  - shocked ejecta, nucleosynthesis products from stellar evolution and explosion
  - shocked circumstellar and interstellar material
  - efficient cosmic-ray acceleration

- **X-ray observations provide unique opportunities to observe, model, and constrain properties of the above using techniques learned in this X-ray Astronomy School**
  - data preparation and reduction
  - image generation and manipulation; energy-dependent structure
  - spectral modeling; emission mechanisms (shock-heated plasmas, nonequilibrium ionization, variable abundances, synchrotron emission, blackbody emission)
  - temporal studies; timing of pulsars

- **The results are rewriting the book on young NSs and SNRs**